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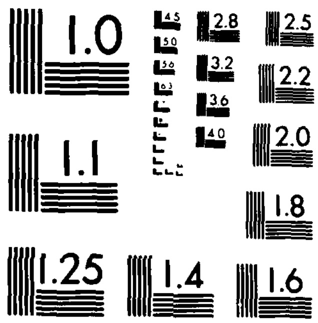

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TOWARD A MODEL OF ATTENTION AND THE DEVELOPMENT OF AUTOMATIC PROCESSING

(12)

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Report HARL - ONR - 8402

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A model for the development of automatic processing is briefly described. The model is a quasi-neural model in which information processing is done through the transmission of vectors between visual, lexical, semantic, and motor processing units. Controlled processing involves gating of the output power of vectors to perform matches and to release response vectors. As subjects practice consistent tasks, associative learning enables an input vector to evoke an output vector and priority learning

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20. Abstract. Cont.

determines the power with which a vector is transmitted. Automatic processing involves a cascade of vector transmissions in which the output power of each transmission is determined by priority learning. The transition from controlled to automatic processing takes place in four phases. Empirical illustrations of the transition are described.

effects in a simple search.

Model Overview

The rationale for the present model comes from three sources: the attention literature, neurophysiology, and communication theory. The attention literature illustrates the shift from serial to parallel processing and the inability to directly control automatic processing (see Schneider & Fisk, 1983; Shiffrin & Schneider, 1977). The present model illustrates how continuous improvements in association strength and message gain can shift processing from a serial to a parallel mode. The model predicts the importance of consistent practice in developing fast, efficient processing (see Schneider & Fisk, 1983).

The neurophysiological literature suggests the structure of the model. Cortical information transmission occurs when a population of neurons (e.g., a hypercolumn) sends a set of firing rates (e.g., a vector of activation) to another population. This set of firing rates of the output neurons can be modulated as a set (e.g., chandelier modulation of pyramidal cell output; see Szentagothai, 1977). The evidence for vector transmission and modulation of vector output power supports the central concepts of the model.

Communication theory provides optimality considerations regarding how best to allocate transmission time in a network of vector transmission units (see Van der Meulen, 1977). Communication theory theorems indicate that if the brain optimally processes information there should be two modes of transmission: a serial, time-sharing, control-process-type mode and a parallel, automatic-process-type mode (see Schneider, 1984).

The present model assumes that processing is done by the transmission of messages between specialized processing units. For example, a semantic choice-reaction-time task (e.g., respond to animal words) would require at least three transmissions. A visual unit transmits visual features to a semantic unit. The semantic unit makes an associative translation to the semantic code and transmits that to a motor unit. The motor unit makes an associative translation of the semantic code to a muscle code and transmits that message to produce a response.

In the model, controlled processing is conceived of as a limited central processing mechanism that gates the transmission of messages between units and compares the received messages. The development of automatic processing is the result of two types of learning. The first, associative learning, is the mechanism by which one message is associatively translated to another message. The second type of learning, priority learning, is the mechanism by which a unit determines how strongly to transmit a message. The unit specific message priority determines the strength of the

automatic message transmission. Automatic processing occurs when priority and associative learning are sufficiently advanced to allow a sequence of transmissions without any controlled-process gating of the information.

The model predicts that the transition from controlled to automatic processing should occur in four phases. The transition between phases is done in a continuous manner depending on subjects' strategies, workload, and skill acquisition. Phase 1 requires memory preloading of message units and controlled processing gating of transmissions. Phase 2 involves Phase 1 operations plus on some trials the automatic transmission of messages evokes a response. Phase 3 involves automatic processing with controlled-process gating assisting in the transmission of messages. Phase 4 involves pure automatic processing of messages without controlled processing.

Structure of the Model

The processing is done by the transmission of vectors between a large number of processing units. The vector transmission could be represented as the frequency of firing a set of neurons (e.g., cortical hypercolumns). For example, a visual unit might transmit a vector which codes dot locations. The letter "E" might be represented as vector of 1s and 0s on a 4 x 6 dot matrix (i.e., "E" = 1111 1000 1000 1111 1000 1111). Similarly, a semantic unit vector codes semantic features (e.g., size, function, category, etc.) and a motor unit codes muscle groups.

The received vector is transformed through an association matrix. The association matrix could be implemented as the set of strengths of connections between the output neurons from one unit and the input neurons to a receiving unit. The transmission of the "E" vector of the visual unit would evoke a character vector (e.g., 10001101... representing letter, not digit, not consonant, vowel, not sound 'a', sound 'e'...). Such an association matrix can encode many associations by storing in the connective strengths the additions of all the individual associations. J. A. Anderson (1977, 1983; Anderson, Silverstein, Ritz, & Jones, 1977) has illustrated how such matrices can produce associative translations (see also below).

The transmission of vectors amounts to the sending of messages between units. The received vector of a unit is the summation of all the individual vectors (component by component) transmitted to the unit. The clarity of a message is determined by the signal to noise ratio (S/N) of the received vector. The S/N is determined by the power of the signal vector divided by the summed power of all the non-signal vectors. This representation allows the prediction of the detection sensitivity of a receiving unit (d') and the reaction time necessary to receive a message (see below).

Toward a Model of Attention and the Development of Automatic Processing

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Technical Report HARL-ONR-8402

Abstract

A model for the development of automatic processing is briefly described. The model is a quasi-neural model in which information processing is done through the transmission of vectors between visual, lexical, semantic, and motor processing units. Controlled processing involves gating of the output power of vectors to perform matches and to release response vectors. As subjects practice consistent tasks, associative learning enables an input vector to evoke an output vector and priority learning determines the power with which a vector is transmitted. Automatic processing involves a cascade of vector transmissions in which the output power of each transmission is determined by the priority learning. The transition from controlled to automatic processing takes place in four phases. Empirical illustrations of the transition are described.

1

Toward a Model of Attention and the Development of Automatic Processing

A fundamental question in attention and learning is "What is the microstructure of skill development?" This paper briefly presents an explicit microstructure illustrating the qualitative and quantitative changes in processing associated with the development of skill.

It is generally agreed that the acquisition of almost any cognitive or motor skill involves profound changes with practice. These changes have impressed researchers since the earliest days of psychology (James, 1890; Solomon & Stein, 1896). Consider, for example, the changes that occur while learning to type. At first, effort and attention are devoted to the smallest movement or minor decision, and performance is slow and error-prone. After extensive training, long sequences of movements or cognitive processes are carried out with little attention. The changes are striking enough that performance of the task seems qualitatively different before and after practice.

A number of researchers have interpreted the qualitative differences between novice and skilled performers as being the result of two qualitatively different forms of information processing (James, 1890; LaBerge, 1976; Logan, 1978, 1979; Neumann, 1984; Norman, 1976; Posner & Snyder, 1975; Schneider & Fisk, 1983; Shiffrin & Schneider, 1977). In this paper the two forms will be referred to as controlled and automatic processing. Controlled processing is characterized as a slow, generally serial, effortful, capacity-limited, subject-controlled processing mode that must be used to deal with novel or inconsistent information (see Schneider & Fisk, 1983). Automatic processing is a fast, parallel, fairly effortless process which is not limited by short-term memory capacity, is not under direct subject control, and performs well-developed skilled behaviors.

At present we have no detailed representation of how the practice changes occur. The models in the literature are generally verbal descriptions of the qualitative changes observed in performance. For example, James described the transition from conscious control to automatic, habitful behaviors (1890). A number of researchers (e.g., LaBerge, 1976; Norman & Shallice, 1980; Shiffrin & Schneider, 1977) discuss the shift from controlled to automatic processing. J. R. Anderson (1982) discusses the shift from an interpretive processing of knowledge to a compiled processing. Pew (1966, 1974) characterizes practice as changing the level of conscious control. MacKay (1982) suggests practice increases the linkage between nodes. Adams (1971) interprets practice effects as shifting from carefully monitored closed loop control to a more automatic open loop. These proposals, however, are too vaguely stated to allow detailed simulations of the learning

Phase 1: Controlled Processing with Memory Set Up (VM)

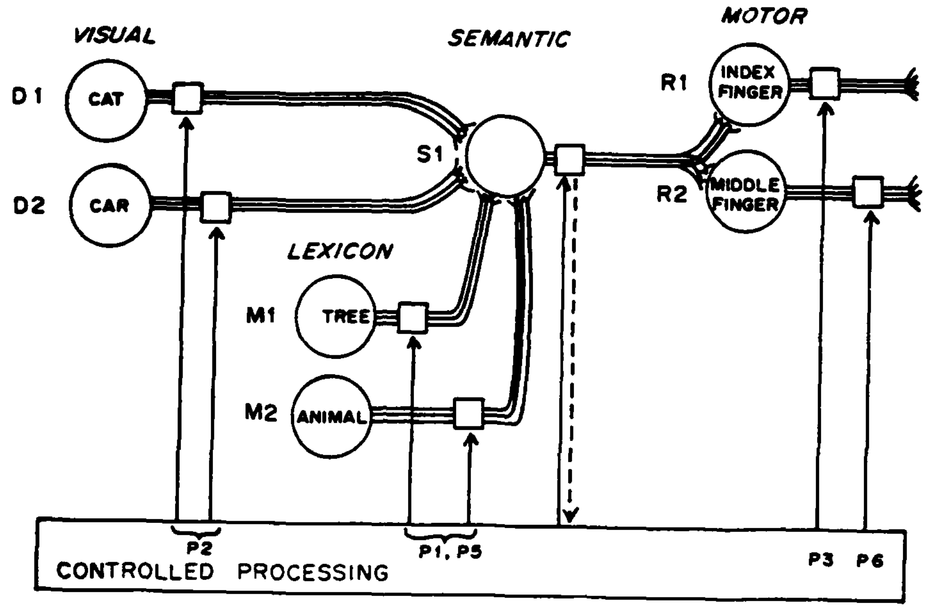

Figure 1. Structure of controlled processing search. The units (circles) (D1, D2, S, M1, M2, R1, R2) transmit vector messages (words in the circle) with a power determined by controlled processing gating (upward arrows and boxes). The received power of a vector is reported to the controlled-processing system (downward dashed arrow). See Figure 2 for operations of controlled processing.

Controlled Processing Operations

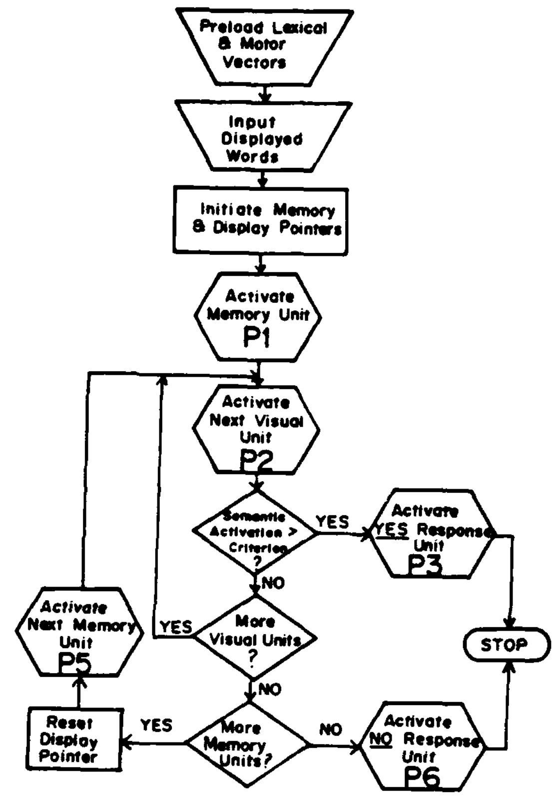

Figure 2. Flow chart of controlled-processing operations during VM category search. The trapezoid shapes represent input to the system; the hexagonal shapes represent controlled-process gating of vector transmissions, the diamonds are conditional tests, and the rectangles are internal controlled-process operations. The "P#" refer to controlled-processing gating referred to in Figures 1 and 3.

Attention is the gating of processing units that influences the power of the transmitted vectors. The output power of a vector is determined by two components. The power of the processing unit can be thought of as the variance of the firing rate of the output neuron. The first is a "central" controlled-process gain, G_{cpu}.[1] It is assumed that a central mechanism sends a scalar, G_{cpu}, to unit u which influences the power of the transmitted vector. The second component determining the power is the automatic-process gain, G_{apum}. The automatic gain is specific to a given unit u transmitting message m. When a unit has a message to transmit, the unit encoded priority of the message determines the automatic gain for that message. The actual total output power is assumed to be determined by a scalar function of the automatic- and controlled-process gains [f (G_{cpu}, G_{apum})]. In the current model, I assume the function is simply the addition of the automatic- and controlled-process gain ($G = G_{cpu} + G_{apum}$). To illustrate, suppose that a visual unit transmits a vector to the semantic unit indicating that the word "CAT" has appeared. If the automatic gain for the word "CAT" in the visual unit has a power of 4 and the controlled-process gain for the visual unit is at a power of 5, the transmitted vector would have a power of 9 times that of the initial vector (e.g., if the vector is [-6,0,+6] with an average power or variance of 24, after gain control of 9, the vector is [-18,0,+18] (since the power squares the elements of the vector, each element of the vector is multiplied by the square root of the power) and an average power of 216).

Controlled processing is accomplished through modifications of the controlled-process gain of units and assessment of the degree of activity of units. The degree of activity is defined as the average power or variance of a received message. The mechanism for changing the controlled-process gain allocated to units is represented as a sequence of steps of a program (see Figure 2) or a series of productions (cf., J. R. Anderson, 1983). These productions amount to "if-then" rules for assessing the degree of activity of a given unit and changing the allocated power of units.

Category Search Procedure

The transition from controlled to automatic processing will be illustrated with examples from a category search experiment. A typical procedure for a category search experiment involves: a) presentation of a short list of memory set categories to memorize (typically one to four); b) presentation of a short list of probe words which may or may not be exemplars from the target categories; and c) a subject response, indicating whether any of the members of the probe words are members of the target categories held in memory. In a "yes/no" variant of the procedure, the subject makes a "yes" response if there is a match between a presented probe word and a memorized target category, and a "no" response if none of the probe words match any of the target categories. In such an experiment

reaction times increase linearly with the number of comparisons. The data are generally interpreted to reflect a serial, self-terminating comparison process (see Fisk & Schneider, 1983).

A critical variable in category search is whether the target and distractor sets are variably or consistently mapped. In a variably mapped (VM) condition, a word which requires a "yes" response on one trial may require a "no" response on the next (e.g., in searching for "ANIMALS," the subject may respond "yes" to the word "CAT," on Trial 1, then while searching for "VEHICLES" on Trial 2, respond "no" to the word "CAT"). In such conditions subjects utilize a serial, slow (200 ms per category), self-terminating comparison process. Performance shows little, if any, change in comparison time as a function of practice (Fisk & Schneider, 1983). In a consistently mapped (CM) condition, the subject always responds to a given category in the same way (e.g, whenever the subject sees the word "CAT", he or she responds by pushing the button with an index finger). Search in CM procedures shows substantial change with practice (see Figure 4). The processing becomes fast (2 ms per category), parallel, and fairly effortless (Fisk & Schneider, 1983).

Phase 1 -- Controlled Processing with Memory Preload (VM Search).

In Phase 1, controlled processing modifies the output power of given vectors and identifies matches on the basis of how changes in the gain influence the degree of activity of particular units in the system. Phase 1 processing is exhibited during initial practice or in tasks in which the stimuli are variably mapped.

Figure 1 illustrates the structure of the model for performing Phase 1 category search. The subject must compare two probe words to two semantic categories and respond with a positive or negative response. It is assumed that before the probe words are presented, the subject is given instructions to preload lexical memory (or working memory) with the category vectors of TREE and ANIMAL, and preload motor response memory with the vectors for pressing buttons with the index finger and the middle finger. When the visual probe stimuli are presented, the display units activate the vectors for the visual representation of the word "CAT" and "CAR". Controlled processing manipulates the gains of the various vectors in order to perform a category comparison match and motor response (see below).

UNIT DISPLAY MEMORY RESPONSE

UNIT	DISPLAY	MEMORY	RESPONSE
1	CAT	TREE	PRESENT
2	CAR	ANIMAL	ABSENT

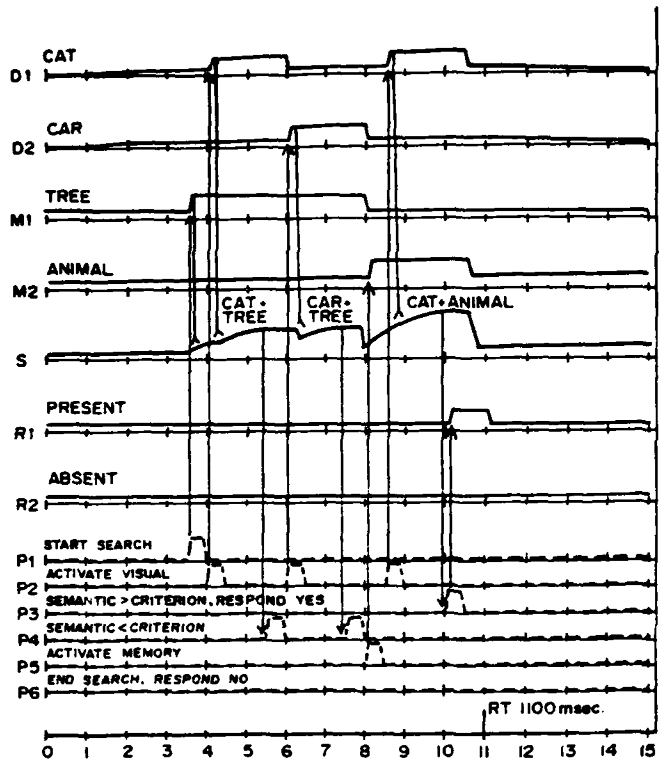

Figure 3. Simulated activity patterns during a variably-mapped category search. The middle of the figure illustrates the output activities of units in the system. The bottom of the figure illustrates controlled-process gating of vector transmissions (see Figure 2). The upward lines indicate changes in gain, the downward solid lines indicates the effects of vector transmission, and the dashed downward lines indicate the report of the received variance from the semantic unit to the controlled-processing system. The bottom axis of the figure indicates elapsed time in 100 ms intervals. See text for discussion of the sequence of operations.

In a variably-mapped condition, subjects' performance is expected to remain in Phase 1 even after extended training. The learning mechanisms (see below) influence performance when there is a consistent relationship between the messages that are sent from one unit to another. In a variably-mapped condition, this consistency is not maintained, and hence little, if any, learning is expected to occur (see Fisk & Schneider, 1983). In a category search experiment (Schneider & Aldrich, 1984) the slope for trials 97-102 was 224 ms per condition, for trials 769-864 the slope was 208 ms with no significant change in slope.

The performance in Phase 1 of the model illustrates the primary characteristics of novice and variably-mapped performance. Performance is slow, serial, and effortful. Performance degrades with increases either in memory load or in processing load and there is little benefit for variably mapped processing.

<u>Phase 2</u> -- <u>Controlled and Automatic Processing (CM)</u>

Phase 2 processing is exhibited in the early development of a skill in which the subject is making consistent responses to stimuli. Phase 2 processing is defined as the co-occurrence of two types of processing. The first type of processing is the Phase 1 controlled shifting of gain and memory preloading. The second type of processing is automatic processing. Automatic processing develops such that when the target semantic vector is transmitted, the semantic vector will associatively evoke the index finger response. The reaction times are assumed to be a mixture of responses from the controlled and automatic processing mode. The observed positive reaction times should be the minimum of the two reaction time distributions.

<u>Associative and Priority Learning</u>

Automatic processing develops as a function of two types of learning mechanisms. The associative learning mechanism modifies the unit to unit associative matrix such that a stimulus vector will evoke an appropriate response vector. This involves a Hebb-type synaptic learning mechanism. J. A. Anderson (1977, 1983; Anderson et al., 1977) has illustrated how vector to vector learning might occur. The interconnections between the elements of the stimulus vectors and response vector change such that the stimulus evokes the response. The equation for change is:

$$\text{delta } A = c(R - AS)S^T \qquad (2)$$

where A is the associative matrix, R the response vector, S the stimulus vector, ST is the transposed stimulus vector, <u>c</u> a learning constant, and <u>delta</u> A is the change in the strength of the

Figure 2 illustrates the controlled-processing operations.[2] Controlled processing, however, maintains information about the goal states in the search, which units have been activated, and the degree of activation of units. Controlled processing does not directly send messages between units; instead it modulates the power of messages transmitted between units.

The degree of match between any two vectors is determined by the evoked power or variance of a received vector. To illustrate, when the gain of the first display unit (D1) is increased, the vector for "CAT" is transmitted to the semantic unit (see Figure 1). When the gain of the second memory unit (M2) is increased, the vector for animal is also transmitted to the semantic unit. The received vector is the sum of the two individual vectors (D1 GD1 + M2 GM2). The variance or power of the received vector is equal to

$$\sigma^2_{D1G_{D1}+M2G_{M2}} = \sigma^2_{D1}G^2_{D1} + \sigma^2_{M2}G^2_{M2} + 2\rho_{D1M2}\,\sigma_{D1}G_{D1}\,\sigma_{M2}G_{M2} \quad (1)$$

In the equation, σ, is the standard deviation, σ^2, is the variance, ρ is the correlation between the two vectors, and G represents the gain. The controlled system identifies a match if the correlation between the two vectors is greater than some criterion (e.g., rho > 0.3).[3] The manipulations of gain of processing units enable the assessment of the correlation between vectors. Thus the output representations of any two vectors can be compared (e.g., by comparing the received variance in a visual imagery unit, the system could determine what the degree of physical match would be between the word CAT and the lexical unit of ANIMAL, or, by comparing the received variance in the semantic unit, the degree to semantic similarity can be assessed).

Figure 3 illustrates the simulated activity patterns during a variably-mapped category search. The reader is encouraged to match up Figures 2 and 3 with the following text. It is assumed that before the trial begins, the M1, M2, R1, and R2 units are loaded with the appropriate vectors. During preloading the subject interprets the instructions, gating messages to activate vectors in appropriate units (e.g., the instructions to respond with an "index finger" would activate the appropriate vector in the motor unit M1). These vectors are decaying with a half-life of 5 s. When the probe words "CAT" and "CAR" are presented, their vectors are evoked in D1 and D2. At 350 ms after display presentation, the first memory unit is activated (P1), transmitting the ANIMAL vector. This results in an additional increase in activation of the semantic unit. At 400 ms, the first display unit is activated (P2), gating the activity of the first display unit. This results in an increase in the activation of the semantic unit. From 400 to 550 ms, the received variance in the semantic unit (S) of the summed vector of D1 + M1 is compared to the criterion (see Equation 1). At 550 ms, the variance

is still below criterion and the comparison is terminated with a mismatch. At 600 ms, the next visual unit is activated (P2), deactivating vector D1 and increasing the power of vector D2. This results in a decrease in the semantic activation from D1 and an increase in the semantic activation from D2. At 750 ms, there is another mismatch between the display and the category vector. At 800 ms, the next memory set item is activated (P5). This results in a decrease in the semantic activation due to the deactivation of "TREE" and an increase due to the activation of "ANIMAL". At 850 ms, the first visual display item is once again activated (P2). This results in an increase in the semantic activation. If we assume that the semantic factor evoked by the word "CAT" correlates 0.5 with the semantic vector evoked by the word "ANIMAL", the activity in the semantic unit would be 1.5 times greater than would be expected by the activation of two orthogonal vectors (e.g., the activation of "CAT" and "TREE"). This increased activity relative to criterion results in the activation of Response 1 vector (P3) at 1000 ms, resulting in the pressing of the "target present" button. The response occurs at 1100 ms.

The sequence of operations illustrated in Figure 3 illustrates a serial self-terminating comparison process with a 200 ms comparison time per category. Note that there are many switches of gains within the processing system. To the extent that such changes in gains are effortful for the subject, this processing represents an effortful procedure.

At this stage of training, any events which either disrupt the preloaded memory vectors or disrupt the operations of the controlled- processing system result in degradation of performance. In variably-mapped search conditions, such degradations of performance are observed. For example, in a letter search task, increasing the memory load of a secondary task interacts with the search memory load resulting in a degradation of performance (Fisk & Schneider, 1983; Logan, 1979). In dual-task conditions, occupying the controlled-processing system by performing a digit search results in substantial degradation of performance of a concurrent variably-mapped letter search task (Schneider & Fisk, 1982a, 1982b) and category search task (Schneider & Fisk, 1983).

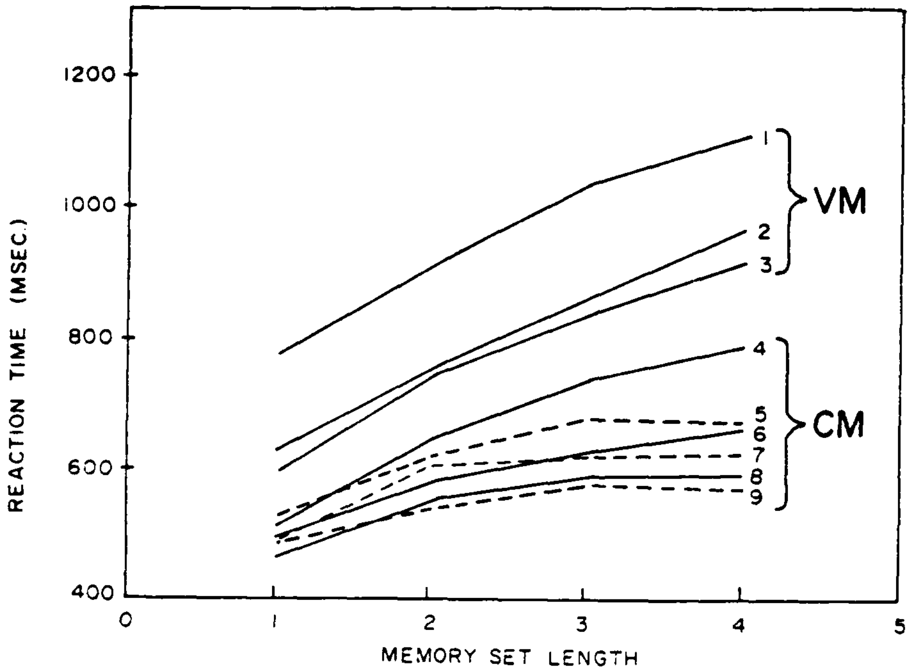

Figure 4. Positive response reaction times for category search memory set size 1-4 categories and a single probe word. Replications of 96 trials with 3 positive probes per category. The first three replications were variably mapped, the last six consistently mapped. Note the flattening for the higher memory set sizes (Schneider & Aldrich, 1984).

Phase 2 processing is a mixture of automatic and controlled processing. Controlled processing is still sensitive to memory and resource load effects. If the subject must perform other tasks requiring memory or controlled-processing resources, performance will deteriorate. As practice proceeds, the automatic processing becomes faster and can complete before the controlled-processing mechanism.

<u>Phase 3</u> - <u>Automatic Processing with Controlled-Processing Assist</u>.

Phase 3 processing is exhibited when sufficient associative and priority learning has occurred such that vectors can evoke vectors without memory preloading. In Phase 3 the memory comparison mechanism is eliminated. The controlled-processing sequential operations (Figure 2) are no longer necessary. The vector evoking process substitutes for the vector comparison process. To illustrate, at this stage of practice the transmission of the "ANIMAL" vector from the semantic to the motor unit (see Figure 1) will associatively evoke the "index finger" response. However, controlled-processing gain is still required in order to have the ANIMAL vector transmitted with sufficient power to overcome the background noise and evoke the "index finger" response vector. The controlled-processing system is assisting the automatic-processing system by allocating the additional power. The complex sequential operations of Phase 1 controlled processing (see Figure 2) are replaced by a single Phase 3 operation of "allocate gain to the display (D1,D2), semantic (S), and motor (M1,M2) units". In this stage, the subject attends to the task in general. For example, in learning to operate a manual transmission, this phase would require the trainee to attend generally to the motor task but not require rehearsal of specific patterns.

Phase 3 processing makes two predictions that have been empirically demonstrated. First, as Phase 3 processing develops there should be a shift from serial to parallel processing. Reaction time, mean, and variance data show a shift to parallel processing in consistently mapped search (see Fisk & Schneider, 1983;Schneider & Shiffrin, 1977, Appendix G). Second, there should be little performance decrement for removal (e.g., through secondary task) of the memory set (except possibly for the very first small memory sets). After extensive CM training subjects can search equally well whether the memory set is presented or not (see Schneider & Fisk, 1982a, 1982b; Fisk & Schneider, 1983; Schneider & Aldrich, 1984).

Whether subjects operate in Phase 2 or Phase 3 is probably dependent on the subjects' strategy (i.e., which controlled processing operation the subject activates). Even after Phase 3 processing may be effective, subjects may still choose a strategy of preloading the memory vectors and performing the serial category

association. Such an associative system can reliably store about as many associations as there are elements of the vector (see Anderson, 1977, 1983). The associations are robust to noise and can produce appropriate responses when only a part of the learned input pattern is presented (Kohonen, 1984).

The associative learning mechanisms require that there be a consistent relationship between the message transmissions in order to develop discriminative associations. To illustrate, assume that the semantic vector of ANIMAL is transmitted to the motor units. If the ANIMAL vector is always transmitted before the index finger responds, the ANIMAL vector will come to associatively evoke the index finger response. However, if on half the trials the animal vector is transmitted immediately before an index finger response and on half the trials it is transmitted immediately before a middle finger response, the ANIMAL vector will not be able to evoke a discriminative response between these two output vectors. In that case, the controlled processing system would still need to resolve which response to output in a manner described in Phase 1 processing.

The priority learning mechanism tunes the unit's transmission so that important messages are transmitted at high gain and unimportant messages at low gain. Equations 3 and 4 illustrate how the automatic gain for a given message changes after a hit and correct rejection.

after hit

$$G_{ap,i+1} = G_{ap,i} + CH\,(G_{apmax} - G_{ap,i}) \qquad (3)$$

after correct rejection

$$G_{ap,i+1} = G_{ap,i} + CR\,(G_{apmin} - G_{ap,i}) \qquad (4)$$

where Gapmax is the maximum automatic gain for a vector, Gapmin is the minimum automatic gain for a vector, CH is the proportional increase in gain after a hit, i is the trial number, and CR is the proportional decrease in gain after a correct rejection. The predicted reaction time as a function of consistent practice produces a power-law-type practice curve (see Schneider, 1984).

If there is a consistent relationship such that certain vectors always result in hits and other vectors always result in correct rejections, the priority learning changes will tune the network so that only stimuli which result in hits evoke transmissions. As a result of this tuning, the target stimuli become foreground and "pop out" of the display. The distractor stimuli become background and, in a sense, disappear from the display. This type of popping out effect is frequently reported by well-practiced subjects in search

experiments (see Shiffrin & Schneider, 1977). In a variably-mapped situation each stimulus has the same probability of hits and correct rejections. Hence, there is no differential priority between stimuli and the priority learning mechanism cannot discriminate which messages to transmit. When the priority mechanisms can not filter the stimuli, it is necessary for the controlled processing mechanism to continue to operate as in Phase 1. Search data illustrate the degree of consistency effect; that is, as consistency decreases, the amount of automatic processing development decreases (Schneider & Fisk, 1982b).

Controlled processing operates as a training mechanism for the development of automatic processing. Controlled processing allows slow, serial, and accurate processing of the stimulus situation. By the use of the memory preloading mechanism, any vector can be compared to a second vector and the results of the comparison allow releasing of a third vector. The comparison activates input and output vectors enabling the associative matrix to develop. Controlled-processing-induced gain-shifts initiate local activation patterns which can produce associative learning. Priority learning occurs following a controlled process transmission. Immediately after a hit or a correct rejection occurs, each unit has a decaying trace of the vector it transmitted. The unit modifies the priority (Equations 3 and 4) of automatic gain for that last transmitted vector.

A number of empirical phenomena are indicative of Phase 2 processing. Automatic processing detections are expected to occur at first in situations where controlled processing is particularly slow. Poorly developed automatic processing transmits vectors at weak power. Weak automatic processes will finish before controlled processing only when many controlled processed comparisons must be made. Thus, there should be a flattening of the reaction time function for higher memory set sizes. With practice, the automatic processing should become faster and hence, the function should flatten at smaller and smaller memory set sizes. Figure 4 illustrates the positive reaction time functions for a category search experiment. The first three replications (96 trials each) were variably mapped (Blocks 1 - 3) and these replications show the expected lack of change in slope in variably-mapped practice. On the fourth replication, the mapping became consistent. Note, by the fifth replication, the reaction times for memory set size 3 and 4 were equivalent.

Empirically, Phase 4 processing is characterized as being robust to the elimination of the controlled processing resources. After sufficient CM practice subjects can perform reliable automatic detection while performing a concurrent high workload controlled processing search (Schneider & Fisk, 1982a, 1982b, 1983, 1984; Fisk & Schneider 1983, 1984).

Phase 4 processing may not operate effectively if the stimuli are severely degraded. If the input vector is severely degraded, a unit cannot identify the vector sufficiently to determine the automatic gain for the vector. To minimize noise in the system, the unit should not transmit a noisy signal. This would predict that consistently-mapped stimulus processing of highly degraded stimuli should not exhibit Phase 4 performance. A number of researchers (Hoffman, Simons, & Houck, 1983; Shaw, 1983; Shaw, Mulligan, & Stone, 1983) have shown that consistent processing of severely degraded stimuli does not show the parallel, capacity-free processing associated with automatic processing.

Even after Phase 4 processing has developed, controlled processing can be used to enhance message transmission. Increasing the power of a message will enhance that message resulting in reduced transmission time and fewer errors. However, total network communications might be hindered by allocating a Phase 4 process additional power for one of two reasons. Giving greater power to one message may interfere with other messages (see Schneider, 1983), or preclude allocating controlled processing power in other messages where it is still required. The second problem with allocating power to an automatic process is the inability of allocating power to a different message that requires it (this assumes that controlled processing can influence the gain of only a limited number of units).

Note that there is no clear transition between Phase 3 and Phase 4 processing. I might operationally define Phase 4 processing in dual task paradigms if two conditions are met. First, performance on the automatic task must be reliable (e.g., > 95% of single task performance level), while the subject is fully engaged in a high resource load controlled-processing task. Second, the subject must maintain the controlled-processing performance at a level comparable (e.g., within 90%) to the single task level. Note the reaction times of the automatic processing might still be substantially increased due to the secondary task prohibiting controlled-processing assist.

Summary

The present model provides a description for the transition from controlled to automatic processing. The transition is assumed to occur continuously through four phases. The proposed phases are

1) controlled processing with memory preload; 2) controlled and automatic processing; 3) automatic processing with controlled assist;and 4) automatic processing. Controlled processing involves the gating of vectors and the assessment of match between vectors. Automatic processing involves a cascade of vector transmissions in which the output power of each transmission is determined by the message unit specific priority. When subjects consistently transmit messages, associative learning causes one message to evoke a new message in a receiving unit; and priority learning determines which messages are transmitted. The present model is sufficiently detailed to allow quantitative simulations of many practice, attention, and search phenomena. Future work will present these fits and novel predictions.

search exhibited in Phases 1 and 2. In some of our experiments a few subjects have exhibited serial controlled processing-type search after many sessions of consistent practice. When these subjects were encouraged to "let go" of the category search, their performance frequently shifted to exhibit behavior suggestive of automatic processing (see Schneider & Fisk, 1983).

Phase 4 -- Automatic Processing

Phase 4 processing will occur in well-practiced consistently mapped tasks. In Phase 4 processing, the associative and priority learning mechanisms have sufficiently developed such that one vector will evoke a follow-on vector without controlled processing. The processing diagram for Phase 4 processing would be simply the visual units outputting to the semantic unit and the semantic unit outputting to a motor unit (basically the top row of Figure 1 with no controlled processing inputs). Figure 5 shows the activation patterns which would be indicative of the automatic processing of the category search experiment. When the words "CAT" and "CAR" are presented, they are assumed to evoke the appropriate patterns in the visual display units, D1 and D2. When the display units are sufficiently activated (e.g., have d' over 2), they identify which vector to transmit on. The word "CAT" is transmitted at a high gain (Gap = 3), becoming foreground information from the display. The distractor stimuli, "CAR," is transmitted on a low automatic gain (e.g., Gap = 1) resulting in it being background information and not influencing the later processing stages. The transmission of the "CAT" vector at 400 ms activates the semantic representation for animal. Once this activation exceeds a criterion threshold (at 450 ms), the unit identifies the automatic gain with which to transmit that message and transmits the message for a brief period of time. The transmission of the ANIMAL vector to the response unit results in evoking the index finger response vector. When this vector exceeds criterion, its automatic gain is determined and that vector is transmitted on, causing the response. This cascade of three transmissions results in a response at 540 ms. The transmission cycle includes associative translation of the received message, assessment of gain, and transmission at the specified gain. Note the complete absence of controlled-processing operations during Phase 4 operations.

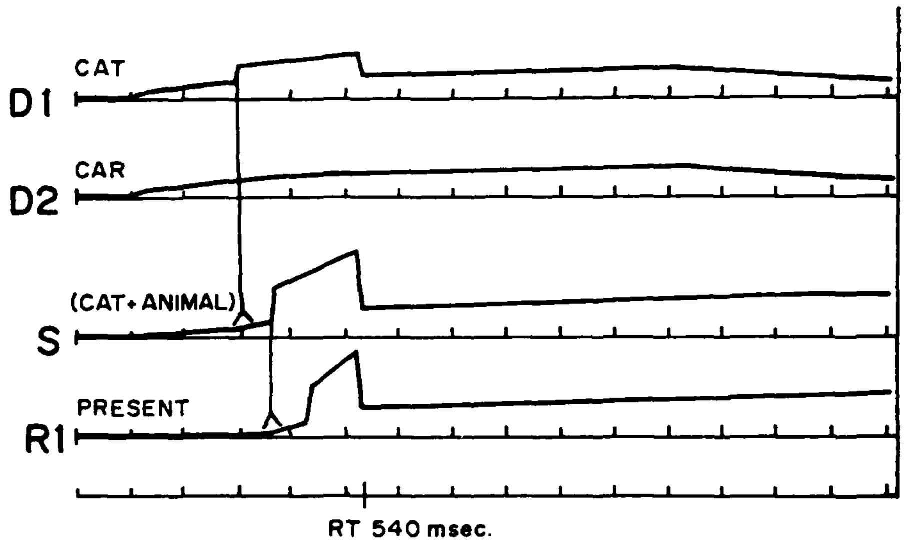

Figure 5. Activity pattern, Phase 4 processing (see Caption Figure 3 for specifications). The gain increases (D1, S, R) are now the result of automatic gain determined by priority learning.

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Footnotes

1. The term "centrally" here refers to a level of processing which controls the cooperative interaction of a population of units. It may be truly central in the sense of one system of the whole cortex. Or it may be partially differentiated in the sense of units for vision, audition, motor control, etc. Also, there may not be a true center but rather the net effect of interactions between units.

2. The controlled-processing operations can be represented as a set of productions (cf., J. R. Anderson, 1983) in which P1 - P6 (Figures 2 and 3) are productions that fire one at a time. However, in contrast to Anderson-type productions, the present productions gate messages but do not directly send messages.

3. Since the controlled processing system sets GD1 and GM2 and if the vectors are normalized vectors, the correlation can be calculated from the variance of the summed vector.

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